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Yellow nanosecond sum-frequency generating optical parametric oscillator using periodically poled LiNbO₃

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Abstract

Nanosecond yellow light has been generated through simultaneously phase matched sum-frequency generation and optical parametric oscillation in a periodically poled LiNbO₃ crystal. 300 mW of yellow light at a wavelength of 586 nm has been generated from 1.3 W of laser power from a Q-switched Yb:YAG laser operating at 1031 nm. The conversion efficiency of the device is 23 %.

PACS: 42.65.Ky Frequency conversion; 42.65.Yj Optical parametric oscillators

1. Introduction

Lasers in the yellow spectral region have many applications within biomedicine due to the high absorption of hemoglobin. Currently the yellow lasers of choice for medical applications are copper vapour lasers at 578 nm and dye lasers operating at 585 nm and 595 nm. These lasers are both bulky and inefficient and it would be attractive to develop a solid-state alternative to these lasers.

One path that has been followed for the generation of yellow light is second harmonic generation of a Raman shifted Nd:YAG laser [1]. In their approach 1.2 W of yellow light at 578 nm was generated at a repetition rate of 10 kHz. Another approach often used to reach the yellow spectral region is sum-frequency generation (SFG) of two neodymium lasers operating around 1064 nm and 1320 nm respectively [2-4]. Many Watts of yellow light have been generated in this way by using external cavity sum-frequency generation of two injection locked lasers [4]. Another potentially efficient method for the generation of yellow light is by employing sum-frequency generation to an optical parametric oscillator (OPO). Recently a nanosecond sum-frequency generating optical parametric oscillator was reported using a single KTA crystal to generate red light at 627 nm [5] and a continuous wave device operating at 629 nm has also been reported based on PPLN [6]. Multistep parametric processes have been known for many years and simultaneous sum-frequency generation in an optical parametric oscillator was first demonstrated by Andrews et al [7]. Recently Figen et al. [8] demonstrated the generation of red light by simultaneous phase matching of both the SFG and the OPO in a KTA crystal and Gao et al. [9] used periodically poled stoichiometric lithium tantalate to generate red-green-blue laser light. Second harmonic generation in an optical parametric oscillator was demonstrated by Ammann et al. [10]. A comprehensive overview of multistep parametric processes is given in [11].

In the present paper, we present a new method for generating light in the yellow spectral region. By using a diode-pumped Q-switched Yb:YAG laser as pump source for a periodically poled LiNbO₃ (PPLN) optical parametric oscillator we generate a signal wave at 1358 nm and an idler wave at 4282 nm. By sum-frequency generation of the pump laser and the signal wave we are able to generate yellow light at 586 nm. 300 mW of yellow power was generated from 1.3 W of input pump laser power corresponding to a conversion efficiency of 23 %. Both the optical parametric oscillation and sum-frequency generation was phase matched in a single crystal containing two different poling periods. We furthermore present observations of secondary optical parametric oscillators pumped by the circulating signal wave and the generated yellow light.

2. Experimental setup

The experimental setup is shown in figure 1. It consists of a diode-pumped Q-switched Yb:YAG laser emitting up to 1.5 W of average power at a repetition rate of 6 kHz. The laser operates at a wavelength of 1031 nm with a spectral bandwidth of approximately 0.1 nm and emits a polarized output with a beam quality parameter $M^2 = 1.2$. The maximum pulse energy is 250 μ J and the pulse duration is approximately 320 ns. The laser is directed through beam steering optics and a focusing lens with a focal length of 100 mm to achieve a beam waist of 65 μ m in the external optical parametric oscillator cavity. The cavity is arranged as a bow-tie ring cavity in order to obtain uni-directional operation and avoid back reflections to the pump laser. The cavity mirrors are two curved mirrors with 75 mm radius of curvature and two plane mirrors. The mirrors are all coated for high reflectivity at the signal wavelengths from 1300-1400 nm and high transmission at the pump laser wavelength, the idler wavelengths (above 3000 nm) and yellow

wavelengths (550-600 nm). The two curved mirrors are separated by 115 mm and the remaining distance in the cavity is 173 mm.

The PPLN crystal is 31.5 mm long, 8 mm wide and 0.5 mm thick and poled with two different poling periods. The poling period for the optical parametric oscillator (OPO) is 26.5 μm and the poling length is 25 mm. The remaining 6.5 mm of the crystal was poled with a period of 8.85 μm to achieve phase matching of the sum frequency generation. The PPLN crystal was AR coated on both ends for the pump and signal wavelengths. The crystal was placed in an oven to control the temperature and avoid photorefractive damage. The optimum temperature for yellow light generation was found to be 193°C. The PPLN crystal was placed in the cavity and oriented such that the pump laser traverses the SFG region of the crystal before the OPO region. In this way the SFG process takes advantage of the undepleted pump laser pulse and the conversion is more stable and efficient [12]. A filter is used to separate the yellow light from the pump, signal and idler waves.

The 1031 nm Yb:YAG laser was chosen as pump source because of the absorption of wavelengths above 4500 nm in LiNbO_3 . The idler wavelength generated by the OPO can be expressed in terms of the laser and sum frequency wavelengths as

$$\lambda_{idler} = \left(\frac{2}{\lambda_{laser}} - \frac{1}{\lambda_{SFG}} \right)^{-1} \quad (1)$$

Where λ_{laser} , λ_{idler} and λ_{SFG} are the laser, idler and sum frequency wavelengths respectively. If we had chosen to use a Nd:YAG laser at 1064 nm to generate light at 586 nm, the signal wavelength would be 1304 nm and the idler wavelength would be 5773 nm. This idler wavelength would experience strong absorption in the PPLN crystal and the OPO process would be less efficient.

The idler wavelength is 4285 nm when using the Yb:YAG laser for the generation of 586 nm light. This idler wavelength only experiences a relatively low absorption in the PPLN crystal.

3. Experimental results

The OPO threshold was found to be 450 mW of average laser power corresponding to a pulse energy of 75 μ J. Using tighter focusing in the PPLN crystal the OPO threshold could be lowered to 10 μ J but the extracted yellow power was considerably lower. The extracted yellow power as function of the input pump power is shown in figure 2. The maximum extracted yellow average power was 303 mW at an average pump power of 1300 mW. This corresponds to a conversion efficiency of 23 %. It is seen that the conversion efficiency seems to saturate at approximately 23 %. The signal wavelength is 1358 nm and the wavelength of the yellow light is 586 nm with a spectral bandwidth of approximately 0.1 nm.

The OPO and SFG processes heavily deplete the laser pulses. A plot of the incoming laser pulse, the depleted laser pulse and the generated yellow pulse is shown in figure 3. The pulse width of the generated yellow pulse is approximately 300 ns. The depletion of the laser pulse reaches 78 %.

The beam quality parameter of the yellow light was measured to be $M^2 = 1.28$ at maximum power, which corresponds well with the beam quality of the pump laser. The power variation of the yellow light was measured to be less than 1.5 % during a 30 minutes measurement. We expect the power stability to increase with a more stable mechanical setup.

The SFG-OPO was also tested with the PPLN crystal turned so that the pump light first traverses the OPO region of the crystal. The maximum extracted yellow power was 75 mW in this

configuration. The reduction in yellow power is caused by the heavy depletion of the pump beam during the pass through the OPO region of the crystal. The second harmonic of the signal wave was on the other hand enhanced in this way due to the high intracavity signal intensity and up to 150 mW of red light at 679 nm has been generated.

We have also tested the SFG-OPO using a 51.5 mm long PPLN crystal containing 44 mm with a period of 26.5 μm and 7.5 mm with a period of 8.85 μm . The maximum extracted yellow power from this device was 235 mW. It was found that the generated yellow power was limited by secondary OPOs pumped by the yellow light and the signal wave. The secondary OPO pumped by the yellow light in third order of the OPO period in the PPLN crystal generated a signal wavelength at 1046 nm and an idler wavelength of 1330 nm, which could resonate in the cavity. The secondary OPO pumped by the signal wave at 1358 nm generated a secondary signal wavelength of 1834 nm and a secondary idler wavelength of 5232 nm. Different parasitic processes in the PPLN generated light at many different wavelengths by up-conversion of the pump laser and the primary and secondary OPO waves. Simultaneously the device emitted light at 5232 nm, 4282 nm, 1834 nm, 1358 nm, 1330 nm, 1046 nm, 1031 nm, 917 nm, 831 nm, 780 nm, 679 nm, 609 nm, 586 nm, 515 nm, 496 nm, 453 nm, 410 nm and 357 nm. No attempts were made to measure the power of the parasitically generated waves.

4. Conclusion

We have demonstrated a simple and efficient method of producing light in the yellow spectral range. By using sum-frequency generation inside the optical parametric oscillator cavity we have generated 300 mW of light at a wavelength of 586 nm with a conversion efficiency of 23 %. Other wavelengths can be generated by a different design of the PPLN crystal. We have furthermore observed secondary optical parametric oscillators pumped by the signal wave and

the yellow light. These secondary optical parametric oscillators limit the amount of yellow power when using a long PPLN crystal.

Acknowledgements

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FIGURE CAPTIONS

Fig. 1. Experimental setup for yellow light generation. The Q-switched Yb:YAG laser is mode matched to the ring cavity and the PPLN crystal contains periods for optical parametric oscillation and sum-frequency generation.

Fig. 2. The extracted yellow power (triangles) and conversion efficiency (squares) as function of the pump laser power.

Fig. 3. Plots of the incoming laser pulse, the depleted laser pulse and the generated yellow pulse from the SFG-OPO.

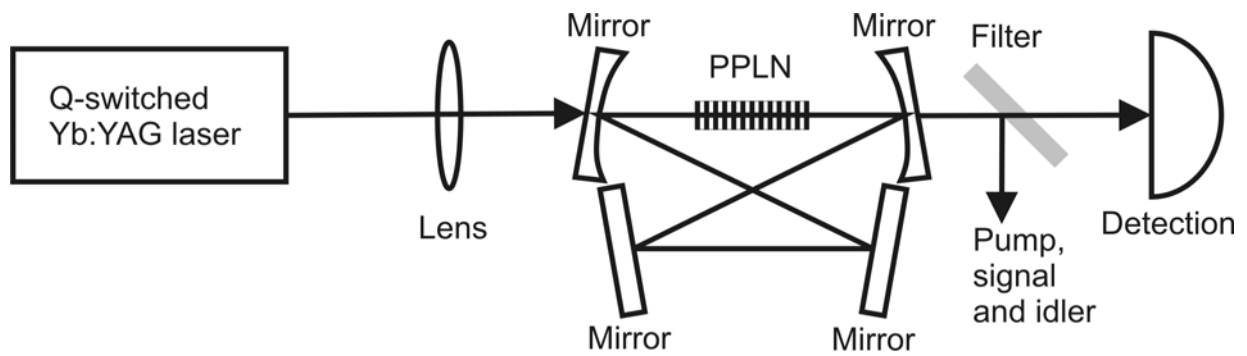


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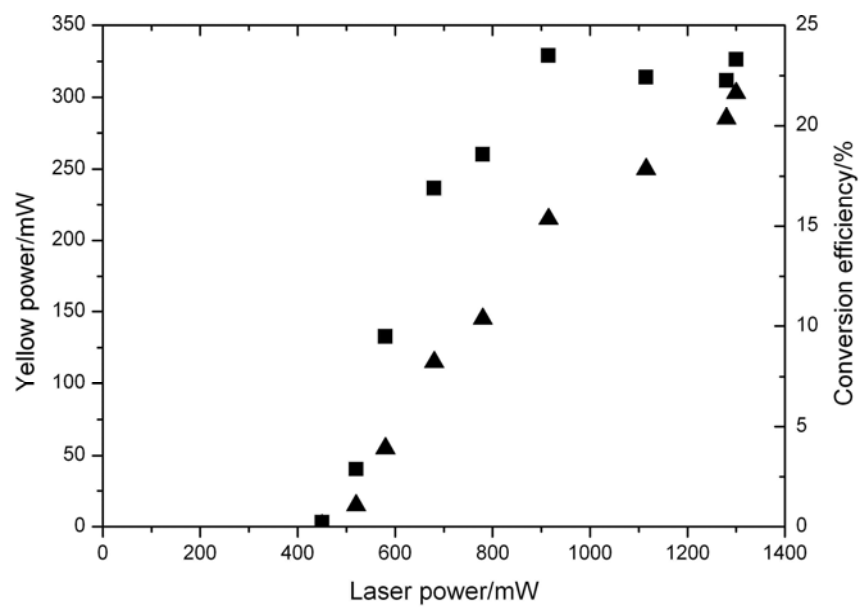


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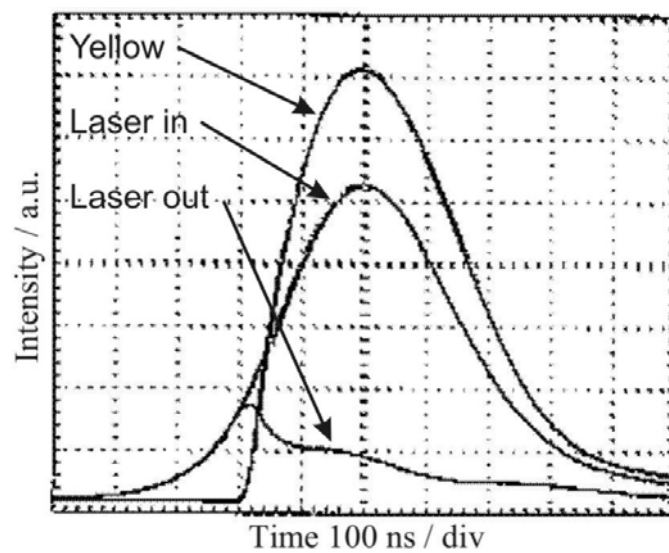


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